New insights into Coronae evolution: Mapping on Venus

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Abstract. Coronae are geologically and geophysically important features on Venus, since they are thought to contribute to planetary heat loss. It is thus necessary to understand their role in space and time in the evolution of Venus. Detailed mapping of five coronae in Guinevere and Sedna Planitia illustrates that although previous models invoked initial uplift, not all coronae can be explained in such a simple way. We show that the formation of corona annuli can be multistaged and that the position of the annulus does not always coincide with the main topographic ridges and troughs that outline the feature. The magnitude and timing of volcanism are not necessarily the same at each corona, and coronae can have long and complex histories, in contrast with the stratigraphic relations suggested by other workers. We demonstrate that coronae do not all have the same relative ages with respect to adjacent units. These results suggest that corona formation was (is) not confined to a single time period in the history of Venus and that detailed mapping is a reliable method of establishing the relative timing of corona formation.

1. Introduction

Coronae consist of concentric annuli of ridges and/or graben [*Barsukov et al.*, 1986; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. Most have a circular or ovoidal planform shape, with maximum diameters of 65 to 2100 km. The topography of coronae varies, with most having a raised rim [*Stofan et al.*, 1992, 1997]. Volcanism is nearly always associated with coronae, the amount and style of which varies both spatially and temporally [*Stofan et al.*, 1992; *Head et al.*, 1992; *Roberts and Head*, 1993].

A number of models have been presented to account for the morphology and formation of coronae. However, current models do not explain the many variations in morphology which are observed [*Stofan et al.*, 1992; *Stofan and Smrekar*, 1996]. Coronae occur in a number of tectonic environments including volcanic rises, the plains and, most commonly, along chasmata systems [*Stofan et al.*, 1997]. Three stages of corona evolution are inferred from previous observations and theoretical models have been developed to explain these observations [*Stofan and Head*, 1990; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. In the first stage of evolution, uplift and volcanism occur accompanied by interior, radial extensional deformation [*Stofan et al.*, 1992; *Squyres et al.*, 1992]. *Stofan and Smrekar* [1996] suggest that an initial voluminous extrusive episode, predating annulus formation, occurs during this first stage. This first stage has been modeled as a rising spherical diapir resulting in uplift and associated deformation consistent with that observed at many coronae [*Stofan et al.*, 1991; *Tackley and Stevenson*, 1991; *Janes et al.*, 1992; *Koch*, 1994; *Koch and Manga,* 1996].

The second stage of evolution involves the formation of an annulus of either ridges and/or graben. During this second stage, it is predicted that the diapir impinges on the lithosphere, flattening and spreading laterally, to form concentric fractures at the rim of a plateau [*Janes et al.*, 1992; *Koch*, 1994]. The third and last stage of coronae formation is considered to involve reduction of topographic relief and continued volcanism. The reduction in relief and production of the outer trough has been modeled as gravitational relaxation [*Stofan et al.*, 1991; *Janes et al.*, 1992]. A second model, proposed by *Sandwell and Schubert* [1992], suggests that during the last part of mantle upwelling, material breaches the lithosphere and emplaces a substantial load on the surface. In time, the lithosphere is "rolled back," and retrograde subduction occurs, forming an annular ridge and trough.

Various stratigraphic and/or absolute age dates have been proposed for corona formation [*McGill*, 1994; *Namiki and Solomon*, 1994; *Price and Suppe*, 1994; *Basilevsky and Head*, 1994, 1995a, b; *Head and Basilevsky*, 1996; *Price et al.*, 1996; *Basilevsky et al.*, 1997]. These studies place the majority of corona formation after that of regional plains and before the large volcanic shields [*McGill*, 1994], with absolute ages calculated at 120±115 Ma [*Namiki and Solomon*, 1994; *Price and Suppe*, 1994; *Price et al.,* 1996]. As coronae have important implications for the internal dynamics of Venus, it is important to better constrain how they form, the contribution they make to Venusian volcanism, and their significance through time.

In this study, five coronae contained within the U.S. Geological Survey Sif Mons mapping quadrangle (V31) were observed to test models of corona formation and global stratigraphy (Figure 1a). Two coronae overlap into the Sedna Planitia mapping quadrangle (V19). *Stofan et al.* [1997] have shown that corona characteristics, such as topography and morphology, are seen to be globally random. Using full-resolution Magellan synthetic aperture radar (SAR) data, the five coronae were mapped and their relations with surrounding units established. Our mapping techniques follow the guidelines of *Tanaka* [1994]. From these observations, we argue that these coronae formed over an extensive period of time and that coronae have a more complex history than the simple three-stage model previously proposed [*Stofan and Head*, 1990; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. This has important implications for modeling the origin of coronae and constructing a global stratigraphy for Venus.

2. Observations of Coronae in Guinevere and Sedna Planitia

The five coronae described are Idem-Kuva, Nissaba, Benten, Heng-o and Silvia. The margins of these and many coronae show two scales of deformation: (1) a broad (25-120 km across), usually discontinuous, topographic ridge with or without a surrounding trough; and (2) closely spaced (5-15 km) arcuate fractures, graben and/or ridges. Throughout this paper, we define the zone of closely spaced structures as the annulus, following previous practice [*Barsukov et al.*, 1986], and the broader scale ridge and trough structures as rim topography. The two scales of deformation can show important information regarding the formation and stratigraphy of a corona and hence often need to be discussed individually. The section below describes the geologic history of each coronae, then its relation with surrounding units.

2.1. Idem-Kuva Corona

2.1.1. Description. Idem-Kuva (25^{0}N, 358^{0}E, Figure 1b) is situated immediately north of the large shield volcano Gula Mons in Western Eistla Regio. It is classified by *Stofan et al.* [1992] as having a concentric morphology dominated by volcanism. The corona measures approximately 280 km in diameter based on the outermost extent of concentric structures. It is circular in plan view, with a 600 m high central domical region which is 100 km across (Figures 1d and 1e) [*Senske et al.*, 1992]. The central domical region has a minor inner depression, the rim of which is delineated by narrow, radial graben. The highest part of the central rise is to the west, where a small central volcano (<10 km in diameter) is situated (Figure 1c). Two radar-bright digitate flows extend to the north of Idem-Kuva. The southwestern flow appears to emanate from a small edifice situated at approximately 24.3^{0}N, 358^{0}E, while the eastern flow originates from graben located at approximately 24.5^{0}N, 358.5^{0}E (marked f1 and f2 respectively, Figure 1c).

The rim topography of Idem-Kuva (the large-scale concentric structure) consists of a well-developed inner trough and ridge to the south, but only a very shallow inner trough and minor ridge to the north; it has no outer trough (Figures 1d and 1e). The southwest rim shows an inner "terraced" topography which coincides with an annulus of arcuate graben concentric to the central mound of Idem-Kuva.

The graben which form the annulus are prominent to the southwest and southeast, on the inner sloping margins of the corona's trough and, to a lesser extent, on the outer margin of the ridge. Some arcuate graben, associated with the southwestern annulus of Idem-Kuva, do not coincide with the larger scale topographic rim but are clearly offset outboard (marked A, Figure 1c). Furthermore, these graben have a different trend to the topographic rim. To the north of the central dome of Idem-Kuva, concentric graben are less pronounced and are considerably shorter (typically less than 25 km) with reduced widths in comparison to those to the southwest and southeast. The presence of arcuate graben which do not conform to the topographic rim of Idem-Kuva (marked A, Figure 1c), and the terracing of the southwestern rim on its inner side are interpreted as evidence of more than one phase of annulus formation.

The oldest materials of Idem-Kuva are relict upstanding plains materials (Idem-Kuva relict plains, labeled ikpr, Figure

1c). We interpret these relict plains as either materials related to an early phase of volcanism associated with Idem-Kuva or uplifted old plains materials which underlie younger regional plains materials [*Copp and Guest*, 1995, 1998]. Three principal phases of deformation associated with corona formation have deformed the relict plains materials; the oldest is represented by arcuate graben forming the prominent southwestern and southeastern annulus. A second phase of deformation produced the closely spaced radial graben fabric to the northwest of the central rise, and finally the northwest and northeast trending graben were formed, crosscutting the earlier structures.

Apart from the annulus graben, two separate fabrics are associated with the formation of Idem-Kuva. First, a deformational fabric consisting of a close-spaced set of radial graben is observed to the northwest of the central rise. This fabric postdates the concentric graben which form the annulus. Second, is an extensional fabric consisting of graben which trend northwest and northeast and are seen to cross each other. This fabric is interpreted to be the youngest, based on crosscutting relations.

Superposed on structures associated with the three sets of extensional structures are the two radar-bright flows, indicating that some volcanism has occurred after annulus formation at this corona. These two flows represent the most recent event in the formation of Idem-Kuva. The flows follow the topography of the corona, curving inward to the north as they flow into the shallow northern annular trough, showing that the rim topography of Idem-Kuva had formed before this volcanism.

2.1.2. Relation with surrounding units. Idem-Kuva has a complex stratigraphic relation with the regional plains materials. The northern edge of the corona displays a sharp contact with regional plains materials (unit pr, Figure 1c) which overlie Idem-Kuva materials. Regional plains materials (pr) breached the minor northern concentric ridge of the corona, resulting in partial flooding of the concentric trough on the northwestern side. This flooding occurred after extensional tectonics deformed the Idem-Kuva relict plains materials (ikpr). Regional plains materials were subsequently superposed by a radar-bright flow from Idem-Kuva (marked B, Figure 1c), indicating that the formation of Idem-Kuva both predates and postdates local plains materials.

As discussed previously, the southern topographic rim of Idem-Kuva is marked by a dense fabric of concentric graben. This fabric is seen to cut flows on the northern margin of Gula Mons, clearly postdating them. This also differs from Central Eistla Regio, where coronae apparently predate large volcanic edifices [*McGill*, 1994] Thus, contrary to observations made by *Senske et al.* [1992] and *Senske and Stofan* [1993], it is clear that Idem-Kuva, at least in part, postdates Gula Mons. Furthermore, graben interpreted to be related to Guor Linea cut the northern summit of Gula Mons and extend to the northwest, where they merge with the annulus structure of Idem-Kuva. Hence Idem-Kuva is considered, in part, younger than Gula Mons.

The above observations indicate that Idem-Kuva has a complex history, originating before and continuing after the emplacement of regional plains materials as well as materials on the north flank of Gula Mons.

2.2. Nissaba Corona

2.2.1. Description. Nissaba Corona (26^{0}N, 355^{0}E) lies directly northwest of Idem-Kuva in Western Eistla Regio (Figure 1b). The corona's topography is irregular in plan view, with a central circular plateau and smaller topographic high to the northwest (Figures 1d and 1f). The northwest-southeast axis measures approximately 320 km, with a north-south axis of 220 km. To the west and southwest, the central rise is surrounded by a trough, which shallows to the east. Outside the trough, to the southwest, is a broad ridge which curves into the central region of Nissaba. The ridge is discontinuous around the corona. No outer trough is observed.

Nissaba shows less annulus deformation than Idem-Kuva, with the annulus again being defined as small-scale deformation in comparison to the larger scale rim topography. The annulus only partly coincides spatially with the rim topography. A fine-scale annulus fabric is seen in the vicinity of 25.3^{0}N, 354.6^{0}E as well as two long graben which cut flows on the southern margin. A later phase of deformation which may or may not be associated with annulus formation is represented by prominent, semiconcentric graben which occur along the east and northeast margin of Nissaba and extend into Sedna Planitia to the north.

An extensive apron of flows (Nissaba flow unit 2, nf2, Figure 1c) is seen on the west, southwestern, and southern topographic rim of the corona. The flows emanate from fractures that surround a circular depression within Nissaba. The flows are up to 100 km long and are radial to the central rise of the corona. A central volcano at 26.0^{0}N, 354.5^{0}E (marked V, Figure 1c) has a radial, ill-defined flow apron which covers a significant portion of Nissaba's northwestern section (Nissaba flow unit 1, nf1, Figure 1c).

As at Idem-Kuva, the oldest unit is plains material, seen within the corona (Nissaba relict plains materials, marked npr, Figure 1c). Although considerably less deformed than the relict plains of Idem-Kuva, these materials are interpreted as having undergone a similar phase of initial uplift. The volcano (marked V, Figure 1c) postdates the relict plains and is itself postdated by the more extensive apron of flows on the western and southern ridge. The flows which drape the western and southern ridge of Nissaba are interpreted as the youngest volcanic materials.

In summary, the annulus deformation is considerably less pronounced than that of Idem-Kuva. Its structures cut the southern and western flows and thus postdate them. The youngest features associated with Nissaba are the semiconcentric graben along the eastern and northeastern margin of the corona. The structures postdate not only the formation of the rim and annulus of Nissaba, but also the emplacement of the regional plains through which they cut. Volcanism has occurred throughout the history of the corona.

2.2.2. Relation with surrounding units. The corona is embayed by regional plains materials (which constitute Sedna Planitia) to the north, northwest and northeast. Embayment of Nissaba by the materials of Sedna Planitia suggests that at least part of the formation sequence of the corona began before the deposition of these plains material, or contemporaneous with it. On the basis of a similar mottled appearance and deformational characteristics, we infer that the Nissaba relict plains materials may represent an uplifted plains unit stratigraphically older than the regional plains materials which form extensive areas of Guinevere and Sedna Planitiae, described by *Copp and Guest* [1995, 1998].

The south and southwest ridge of Nissaba corona acts as a topographic barrier to Sif and Gula flow materials, and thus existed before emplacement of these flows. Furthermore, a small inlier of Nissaba material surrounded by Sif flow materials is observed (marked I, Figure 1c). To the southwest, flows which erupted from fractures associated with Nissaba (nf2, Figure 1c) are overlain by Sif Mons flow materials. However, at the southern margin of the corona, Nissaba flow materials have a more ambiguous relation with surrounding units. Some Nissaba flow lobes may postdate adjacent early Sif or Gula Montes materials, suggesting that Nissaba late-stage volcanism may postdate emplacement of some Sif and Gula materials.

Nissaba is cut by approximately east-west trending graben that are associated with Idem-Kuva. This places the formation of Nissaba before this later stage deformation of Idem-Kuva.

2.3. Benten Corona

2.3.1. Description. Benten Corona (Figure 2a), 14.2^{0}N, 341^{0}E, is classified as an asymmetrical corona with extensive volcanism [*Stofan et al.*, 1992]. We divide the volcanic materials into four distinct units. These are Benten flows 1, 2, and 3, and Benten edifice field materials (labeled bf1, bf2, bf3 and bef respectively in Figure 2b). The corona has a kidney shaped interior with a maximum diameter of 320 km and is partly surrounded by a prominent broad outer arcuate ridge on its eastern and northeastern margin. The annulus of compressional ridges is dominantly on the inward facing slope of the broad arcuate ridge (Figure 2b). The southern end of the arcuate ridge terminates at the edge of a flooded graben, which is 50 km wide and at least 110 km long. The margins of the graben are delineated by a series of smaller northwest-southeast trending graben. The corona's western margin is composed of a linear ridge trending north-northeast crosscut by numerous graben oriented radially to the corona. Benten lacks a prominent outer trough (Figures 2c and 2d).

The interior of Benten is an irregular hollow which is lower than the outer arcuate ridge of the corona, but at a greater elevation than the surrounding regional plains (Figure 2c and 2d). The floor of the hollow is undulating and deformed by an extensive north-south trending graben system. These graben are partly embayed by the Benten edifice field unit (bef, Figure 2b) at the southern margin of the central depression. To the southeast, Benten edifice field materials are topographically confined within the large graben. No evidence of early stage radial deformation is observed at Benten Corona.

The formation of Benten is interpreted to have begun with substantial volcanism. Two of the three principal flow units, Benten flow 1 (bf1) and Benten flow 2 (bf2), are interpreted to be the result of early voluminous phases of volcanism occurring before or coeval with the formation of the annulus because the annulus and topographic ridge deform both of these flow materials. Benten flow 2 materials form the northern interior floor of Benten. After the formation of the annulus, a third less extensive phase of volcanism resulted in the emplacement of digitate flows (Benten flow 3, bf3) to the east and west of Benten. Bf3 is inferred as the youngest of the three exterior flow units. They overlie the annulus structure and are topographically controlled by the large scale ridge. The flows come from young radial graben located on the western and southeastern margins the corona. The Benten edifice field unit postdates bf3 and is interpreted as the youngest unit.

2.3.2. Relation with surrounding units. The large-scale flow units associated with Benten Corona (bf1 and bf2) are superposed on the regional plains materials of Guinevere Planitia (unit pr, Figure 2b) to the south, and older mottled and lineated plains (unit plm, Figure 2b) to the northwest. The flows also overlie plm materials to the northwest, for example in the vicinity of 16^0N, 337^0E. To the southwest of Benten lies an extensive edifice field, with numerous edifices and associated flow materials. Flows from the edifice field are superposed on bf1 materials but are overlain by bf3 materials.

Topographic data show four smaller coronae (all less than 150 km in diameter) near Benten Corona (Figure 2b, marked Chiun Corona, and unnamed coronae A, B, and C). The largest of the these coronae, Chiun, lies to the north and has a diameter of 130 km. It has a depressed interior. Coronae A has an ovoid shape with a prominent southwestern topographic rim in the form of a ridge. This ridge displays less deformation than the main ridge of Benten; the deformation is mainly confined to the outer facing slope.

Chiun and the three smaller coronae may or may not be related to Benten. However, Chiun must have existed prior to the extrusion of bf2 materials, since they embay Chiun deformational structures. In contrast, the unnamed corona deforms bf2 materials, thus postdating them.

Our observations indicate Benten flow materials are younger than the surrounding plains materials which constitute Guinevere Planitia. Whether Benten Corona began forming before the regional plains of Guinevere Planitia is not known; older units may have been subsequently covered by younger plains material. Flow units associated with Benten Corona do record a sequence indicative of varying amounts and styles of volcanic activity with time. The style of volcanism has changed from voluminous flood lavas to a less extensive digitate flow morphology with a variable backscatter, similar to the sequence observed at other coronae [*Stofan and Smrekar*, 1996]. We interpret the changing style and magnitude of Benten volcanism to indicate a gradual depleting magma reservoir.

2.4. Heng-o Corona

2.4.1. Description. Heng-o Corona in southern Guinevere Planitia (2.0^0 N, 355.5^0 E) is the second largest corona on Venus with a mean diameter of 965 km. It was originally classified as an older, isolated corona with a medium amount of associated volcanism [*Stofan et al.*, 1992, 1997]. Heng-o extends from the V31 quadrangle into the V43 quadrangle to the south [*Greeley et al.*, 1994].

Heng-o is approximately circular in plan view and has varying amounts of deformation around its margin (Figures 3a and 3b). The simplest large-scale rim structure is on the western side. Here the large-scale rim topography is composed of a ridge, which has little elevation above the floor of the corona (typically less than 600 m) and which has a narrow band (typically 12 km across) of lineations along the summit. No inner or outer trench is observed here.

The southern topographic rim is a double ridge and trough (Figures 3c and 3d). The outer ridge displays an annulus of two sets of intersecting graben. Both sets terminate at the summit of the outer ridge and are not seen within the troughs. The double ridge and trough topography and associated cross-latticed graben annulus decrease to the west and northwest along the margin. To the east and southwest, fragments of old embayed graben and ridge structures are observed (Figure 3b, marked A and B).

The northern rim topography is demarcated by a prominent ridge with an inner and outer trough (Heng-o Chasma, Figures 3c and 3d). Annulus deformation in the form of compressional ridges is concentrated approximately halfway up the north facing flank of the ridge. Continuing up the ridge, narrower concentric ridges are observed. The main ridge rises approximately 1 km above the local topography. The crest of the ridge displays another fabric, which is made up of thin lineations oriented radially to the corona.

A number of volcanic centers lie within the rim of Heng-o, including central volcanoes and small shields and cones. There are three major central volcanoes (Heng-o volcanic centers 1, 2, and 3, labeled hv1, hv2 and hv3, Figure 3b). Hv1 is an edifice at least 100 km across with a 60 km diameter caldera deformed by intense northwest trending graben. Associated with this volcano are clusters of small shields. Hv1 materials are overlain by flows from hv2 (Figure 3b) which itself is cut by north-northeast trending fractures. These fractures formed after the set which trends northwest, and cut hv1 materials. Both fracture sets are oriented obliquely to the rim and annulus and do not parallel regional plains structure. Hv3 has a prominent apron of flow materials, the distal margins of which are superposed on the fractures that cut the volcano hv2.

From our observations, the stratigraphy of Heng-o involves a number of phases of volcanism and deformation, but the majority of the corona appears to be composed of regional plains materials. Hv1 is interpreted as the oldest volcanic unit (hv1, Figure 3b). Hv2 formed next, followed by hv3; each phase of volcanism probably overlapped in time. The two belts of deformation which cut hv1 and hv2 are oblique to and do not cut the rim topography of Heng-o; hence it is difficult to establish their relation to Heng-o.

How do the above phases of volcanism relate to the annulus and topographic rim formation of Heng-o? The large volcano hv1 situated in the southeast quadrant of the corona apparently formed during the early stages of corona formation, since it is deformed by graben confined within the corona. An age relation between hv1 materials and the annulus cannot be established, since they do not coincide. The southwest margin of materials associated with hv2 appear to be topographically controlled by the rim of Heng-o. The western volcano hv3 appears to have flows which bank up against the western ridge, hence postdating its formation.

2.4.2. Relation with surrounding units. Heng-o is relatively rare among coronae in that it occurs distant from chasmata or large topographic rises [*Stofan et al.*, 1997]. The relation that the rim of Heng-o has with the surrounding materials is critical in establishing its stratigraphic position. To the north and south, it is possible to trace regional plains materials (unit pr, Figure 3b) over the rim topography inward toward the center of the corona; the rim topography clearly deforms the plains materials and hence is younger at these locations. Older structures proximal to the main rim topography are concentric and are embayed by regional plains materials (Figure 3b, A and B). These materials are interpreted to represent an earlier annulus at Heng-o, suggesting that, as at Idem-Kuva, more than one phase of annulus formation has occurred. While some minor volcanism associated with hv1 postdates the regional plains, the age relation between the plains and hv1 is obscured by dense fracturing which cuts both units.

The northern rim topography described above terminates to the northwest at a smaller corona. Averaging 375 km in diameter, Beltis Corona (provisional IAU name) is defined by semicircular rim topography in the form of a ridge. The rim topography lacks annulus deformation. The floor of Beltis is undulating (Figure 3c) and displays a number of different styles of volcanism, including calderas and numerous small edifices. Volcanic deposits extend from Beltis Corona (bf, Figure 3b) to the northwest margin of Heng-o. The flows postdate the regional plains materials and are topographically controlled by the western rim topography of Heng-o. However, it is apparent that structures associated with the southwestern margin of Heng-o have cut the flow materials and hence postdate them. This represents further evidence for multiple-stage annulus formation at Heng-o.

While it is not possible to precisely ascertain the earliest phase of the development of Heng-o, it is apparent that the present topographic rim and annulus are younger than previously suggested [*Sandwell and Schubert,* 1992]. As with the other coronae in this study, Heng-o has a complex structural and volcanic history rather than representing a discrete event in time.

The style of interior volcanism has remained constant over time, i.e., three phases of volcanism have each produced an edifice with associated flow materials. This is in contrast to the evolution in volcanic style seen at other coronae (e.g., Benten Corona).

2.5. Silvia Corona

Silvia Corona (provisional IAU name), 12.5^{0}N, 355.5^{0}E (Figure 4a) has a mean diameter of 300 km and is approximately circular in plan view. The corona has a prominent northern and southern topographic rim in the form of ridges (Figures 4c and 4d). Lower topographic ridges are observed to the east and west; no internal or external trough is observed. The interior stands higher than the regional plains and has a highly irregular undulating topography (Figures 4c and 4d). Interior materials have a mottled appearance in the radar image. Weakly defined concentric fractures coincide with the northern and northwest rim topography.

In contrast to the other coronae studied here, no coronae related volcanism is seen superposed on regional plains material and little evidence exists for any internal volcanism, except for a few small (<10 km) calderas. However, it is conceivable that any early stage volcanism has been superposed by the surrounding regional plains. No prominent early internal deformation is observed. The interior is interpreted as older plains materials which have been uplifted prior to the formation of the topographic rim by which they are deformed (Figure 4b). The regional plains which surround the corona embay the older internal materials and are also deformed by rim topography (Figure 4b). A number of wrinkle ridges which are pervasive throughout the regional plains are seen to cross part of the western margin of Silvia and hence are presumed to have formed after or contemporaneous with the corona rim [*McGill*, 1994].

From the above observations, we conclude that Silvia Corona began forming prior to the emplacement of the regional plains of Guinevere Planitia. A period of initial uplift has resulted in the preservation of older plains materials within the corona's interior which were subsequently embayed by regional plains materials. Deformation continued after regional plains emplacement, with the formation of a discontinuous topographic ridge and weak fractures seen to coincide with the northern rim topography. No late stage volcanism is observed.

3. Discussion

3.1. Implications for Corona Evolution

Most models of corona formation are based on a three-stage sequence [*Stofan and Head*, 1990; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. While this three-stage sequence is a useful generalization and does apply well to some individual features, some coronae have a much more complex, and currently unmodeled, evolution. *Stofan* [1995] described the variations of corona topography and noted that current models do not account for all the topographic forms observed. How well does the current three-stage evolutionary sequence of corona formation proposed by *Stofan and Head* [1990] fit the five coronae studied here?

3.1.1. Stage 1: Uplift and interior deformation. Initially, coronae are proposed to go through a sequence of uplift with interior deformation and volcanism [*Stofan and Head*, 1990; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. The coronae studied here have interiors which have been modified by varying amounts of deformation; Benten and Heng-o show the greatest amount of interior deformation, while Idem-Kuva, Nissaba, and Silvia show relatively little. However, the timing of deformation is not always associated with the initial formation of the corona. For example, the interior deformation at Benten postdates rim topography formation.

Idem-Kuva, Nissaba, and Silvia Coronae all contain materials which are interpreted to be older than the regional plains materials surrounding them. These materials are interpreted to be uplifted and subsequently deformed by later stages of corona development. We see no evidence of preserved early stage uplifted materials at Heng-o. Although early stage extensional features are present, the interior of Heng-o is not higher than the surrounding plains. We interpret this to indicate that Heng-o has not undergone uplift at any stage in its evolution. At Benten Corona, no early stage deformational features or materials are identified. Benten does have a large amount of associated volcanism. While Benten may have experienced some amount of uplift, volcanic construction could account for the majority of its topography. The initial phase of corona formation has been modeled as a rising diapir with uplift and radial extension [*Stofan et al.*, 1991; *Janes et al.*, 1992]; our results indicate that uplift can occur, but in widely varying amounts, and that early stage interior faulting does not occur at all coronae.

The amount of early stage volcanism identified at each corona varies considerably. Benten Corona has two extensive flow fields which were subsequently deformed by annulus formation. Heng-o has a less extensive amount of early stage volcanism in the form of large edifices. Idem-Kuva, Nissaba, and Silvia Coronae do not have exposed old volcanic units but are embayed by regional plains materials that may cover early stage corona flows.

3.1.2. Stage 2: Annulus formation. The formation of the annulus and possibly a surrounding trough is associated with the second stage of corona formation [*Stofan and Head*, 1990; *Stofan et al.*, 1992; *Squyres et al.*, 1992]. All five coronae have some degree of annulus deformation, and as with interior deformation, the amount and style differ considerably between coronae and within an individual corona. The deformation is predominantly graben, although compressional ridges are seen, for example, on the eastern ridge of Benten. Evidence also exists for more than one annulus-forming event at Idem-Kuva and Heng-o Coronae. These observations imply a more complex sequence of events, with annulus formation possibly occurring in multiple events not necessarily confined to the middle or late stages of corona evolution. Late stage radial graben observed at Benten postdate the annulus and may reflect a secondary phase of uplift [e.g., *Stofan and Smrekar*, 1996].

Coronae are defined by their concentric annulus of ridges and/or graben [*Barsukov et al.*, 1986]. However, most corona also have an annular rim of raised topography. How does the annulus deformation relate to the larger scale topographic ridges and troughs, and in particular, which came first? The two scales of deformation are thought to occur contemporaneously during the middle stage of corona evolution; however, the precise timing is ambiguous. No evidence from observations of combined topographic and SAR data of the five coronae resolves the timing to a greater accuracy, although as stated above, more than one phase of annulus formation and a protracted topographic rim history is apparent at some coronae. At others, the topographic rim formed with little or no associated small-scale deformation structures (e.g., Silvia). Initial work by *Tapper* [1997] suggests that there may be a large number of circular features with an annular rim but lacking concentric ridges and/or fractures, suggesting that the number of coronae on Venus has been underestimated.

3.1.3. Stage 3: Corona relaxation and the correlation of coronae relief with age. Previous work suggested that coronae interpreted to be older have low relief and late stage volcanism [*Stofan and Head*, 1990]. All the coronae, apart from Silvia, have associated volcanism that postdates annulus formation. However, observations of topographic profiles for the five coronae in our study area show no correlation between age, absolute relief, and the complexity of relief. Furthermore, the amount of relief at each corona studied here is similar and does not show a great variation, typically 1 km or less. Heng-o has low relief, the main annulus deforms the youngest major plains unit, and hence postdates it; thus the corona is interpreted to be relatively young. Idem-Kuva, which began formation prior to the regional plains, has greater relief than Heng-o. Therefore, on the basis of this limited study, we find little evidence to suggest that relief can be used to characterize any particular stage of corona evolution, contrary to *Sandwell and Schubert* [1992]. At the coronae studied here, the amount of relief at any individual feature is more strongly controlled by the amount of deformation and/or volcanic construction that has taken place. For example at Benten, volcanism is probably a significant contributor to topography, while at Heng-o and Idem-Kuva, topography is likely to be dominantly the product of uplift or annular deformation rather than construction. Janes and *Squyres* [1995] demonstrated that corona topography could be supported by isostatic buoyancy and flexure of the lithosphere, consistent with the observation here that height is not a reliable indicator of corona age.

The last two stages of corona evolution have been modeled as the formation of a plateau followed by gravitational relaxation [*Stofan et al.*, 1991; *Janes et al.*, 1992; Janes and *Squyres*, 1995]. With the exception of Benten, none of the coronae studied here has a plateau shape. Some have an upraised rim (Heng-o), while others have a ridge encircling an inner dome-shaped topographic high (Idem-Kuva, Nissaba). This diversity in corona morphology is seen on a global scale [Stofan et al., 1997]. In addition, formation and relaxation of a plateau have also been called upon to form the corona annulus [*Stofan et al.*, 1991; *Janes et al.*, 1992; *Janes and Squyres*, 1995]. However, corona annuli exist in coronae with widely varying topographic forms. We interpret this evidence to indicate that the plateau stage may not be as significant as proposed previously, and may not occur at all coronae. Furthermore, widely varying corona topographic forms and multiple-stage annulus formation provide evidence that some coronae go through a more complex evolutionary process than previously suggested. A few of the shapes of coronae could be explained by the stalling of a neutrally buoyant *diaper [Koch and Manga*, 1996]. However, *Smrekar and Stofan* [1997], who include the effects of pressure and temperature-dependent viscosity, pressure-release melting, and a residuum layer in their upwelling model, can model the complete diversity of corona forms, as well as explain multiple-stage annulus formation.

3.2. Implications for Corona Stratigraphy on Venus

Some workers have suggested a specific age of formation for coronae on Venus using both local stratigraphic relations [*Basilevsky and Head*, 1994, 1995a, b; *Basilevsky et al.*, 1997] and crater density statistics [*Price and Suppe*, 1994; *Namiki and Solomon*, 1994; *Price et al.*, 1996]. We now consider the application of these global models to specific areas.

3.2.1. Dating coronae using local stratigraphic relations. *Basilevsky and Head* [1994, 1995a, b] have defined three stratigraphic units associated with coronae based on observations from 36 randomly distributed sites. Each unit is characterized by the structure present. The oldest unit as classified by *Basilevsky and Head* [1994, 1995a, b] and *Basilevsky et al.* [1997] is interior radial or chaotic deformation interpreted to form early in the development of coronae (COdf). The ridges of corona annuli (COar) form the second global unit, and the youngest unit (COaf) is made up of fractures of corona annuli. *Basilevsky and Head* [1994, 1995a, b] and *Basilevsky et al.* [1997] argue that each of the stages of corona evolution represented by these three units is normally contemporaneous on a global scale. We do not observe any simplistic relations between structural deformation and time at the five corona studied here. For example, two of our coronae show evidence of more than one phase of annulus formation. Some corona annuli are younger than the regional plains (e.g., Heng-o) while others are older (e.g., Nissaba). Similarly, interior deformation is not always relatively old at the coronae studied here (e.g., Benten). The different stages of corona evolution were not simultaneous in this region, nor were the same processes repeated at a single corona. Our results indicate that it may be premature to establish global stratigraphic units for coronae; the initial proposed scheme of *Basilevsky et al.* [1997] is not consistent with our observations.

We have established that three (Nissaba, Idem-Kuva and Silvia) of the five coronae began forming before the materials of the regional plains in our study area were deposited. Deformation and volcanism at Idem-Kuva have continued after the formation of Gula Mons. While some coronae may predate large shields [*McGill*, 1994], our studies indicate that simplistic relations between the relative ages of coronae and large volcanoes [i.e., *Price et al.*, 1996; *Namiki and Solomon*, 1994] should be used with caution.

3.2.2. Dating coronae using crater statistics. *Phillips et al.* [1992] calculated that the minimum area needed to produce statistically meaningful crater densities for a planet which has 891 craters is approximately 5 X 10^6 km^2. Only Artemis Corona is large enough to meet this criterion. In order to overcome the problem of corona surface areas being too small to produce meaningful ages using crater densities, an area-weighted mean was used in the dating model of *Price et al.* [1996]. As Price et al. state, this is inherently problematic because where the surface areas of coronae are combined, any range in ages will be smoothed. Hence, although an average age for coronae has been calculated, the shape of the age distribution curve and its span are not known. A further problem is that 319 coronae, 89% of the population, contain no impact craters [*Namiki and Solomon,* 1994].

The average age for coronae calculated by *Price et al.* [1996] is 120 ± 115 Ma, compared with an age of approximately 300 Ma for the plains. However, we find that coronae formation both predates and postdates the regional plains units (e.g. Idem-Kuva). The five coronae studied here have complex geologic histories indicating that they formed over long periods of time. Thus, although calculating an average age for coronae using global crater densities is possible, the use of the results may be misleading, first, because an individual corona can have a long life span, and second, because coronae have formed at different times in the history of Venus. Detailed stratigraphic studies are necessary to correctly determine the relative ages of coronae.

The *Price et al.* [1996] model assumes that cratering is spatially random and rate-constant since the emplacement of the plains and that volcanism and tectonism occurred "simultaneously and instantaneously within a terrain." While the first assumption may hold, the second is a substantial idealization which *Price et al.* [1996] recognize but still employ. The long period of extrusion of flows associated with Benten is an example that this second assumption is not the case at every corona.

Even if the issue of averaging ages is neglected, in order to calculate a meaningful crater density for coronae, it is of utmost importance to map all the materials which are associated with each corona. *Namiki and Solomon* [1994] obtained crater densities for coronae by counting the number of craters which fell within the annulus. As *Price et al.* [1996] indicate, errors in mapping can have a significant effect on the crater density and hence age of a unit; a reduction in area by as little as 10% for the combined area of large volcanoes can result in the crater density of the unit being overestimated by a factor of 2. Therefore, if large sheet flows which are seen to be associated with many coronae [*Stofan and Smrekar,* 1996] are not accounted for, grossly incorrect ages will be calculated.

4. Summary and Conclusions

We find that, while the previously proposed three-stage model for corona evolution is useful, corona evolution can be much more complex. We find that not all coronae undergo initial uplift and that not all coronae may go through a plateau-forming stage. Annulus formation was previously thought to occur during the second stage of corona formation, however, evidence for multiple annuli at Idem-Kuva and Heng-o Coronae suggests that it could occur early in the evolution of the coronae and go through multiple cycles. In addition, annulus formation and rim topography formation do not necessarily coincide in space and time, again indicating that both large- and small-scale deformational processes at coronae can be protracted and may not be confined to a single stage.

The amount and style of volcanism associated with the coronae studied here vary considerably. Predicted early stage volcanism is not observed at Idem-Kuva, Nissaba or Silvia Coronae. Benten Corona has multiple phases of volcanism, with a decrease in volume and change in style over time. Heng-o apparently lacks voluminous early stage volcanism and is dominated by central edifice-style volcanism.

We find the use of global-scale stratigraphic units at coronae to be problematic; coronae in the region studied did not form simultaneously, did have a complex, protracted history, and were not affected by the same processes in the same order. This study also highlights the potential problems in applying globally derived average ages to individual coronae. Continued detailed mapping studies of Venus are required to accurately determine the relative ages of coronae.

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Figure 1a. Location map for the five coronae in the study area. Contour interval is 1 km. IK, Idem-Kuva Corona; N, Nissaba Corona; B, Benten Corona; H, Heng-o Corona; and S, Silvia Corona.

Figure 1b. Magellan image of Idem-Kuva (IK) and Nissaba Coronae (N). Nissaba Corona shows little annulus deformation compared with Idem-Kuva. The southern annulus of Idem-Kuva cuts into, and hence postdates, the northern flank of Gula Mons (G). In the north, both coronae are embayed by local regional plains materials (pr); however, two flows with relatively strong radar backscatter, associated with Idem-Kuva, postdate the plains materials. S marks flow materials from Sif Mons (taken from C1-MIDR 30N351).

Figure 1c. Sketch map of Idem-Kuva and Nissaba Coronae. The approximate boundary between Idem-Kuva relict plains materials (ikpr) and flow materials from Gula Mons is shown with a dashed line. Possible origins for the Idem-Kuva flow materials are marked f1 and f2. Graben at A are offset from the main topographic deformation. Materials at B are interpreted as regional plains materials (pr). I indicates an inlier of Nissaba flow material.

Figure 1d. Topographic profiles of Idem-Kuva and Nissaba Coronae. These and other profiles were constructed from the

Global Topographic Data Record (GTDR). Idem-Kuva has a prominent central rise, while Nissaba has a central depression.

Figure 1e. Topographic map of Idem-Kuva Corona. Line corresponds to topographic profile in Figure 1d.

Figure 1f. Topographic map of Nissaba Corona. Line corresponds to topographic profile in Figure 1d.

Figure 2a. Magellan image of Benten Corona and associated flow materials. The circular feature at the top of the image is Chiun Corona (portion of C1-MIDR 15N335).

Figure 2b. Sketch map of Benten Corona. A, B, and C mark the locations of smaller coronae mentioned in the text. Three distinct flow units are associated with Benten Corona.

Figure 2c. Topographic profiles of Benten Corona. Profile A shows an E-W section highlighting Benten's central depression and prominent eastern ridge topography. Profile B also shows the central depression and the two smaller coronae to the SW marked A and B in Figure 2b.

Figure 2d. Topographic map of Benten Corona. Lines A and B correspond to topographic profiles A and B in Figure 2c.

Figure 3a. Magellan image of Heng-o and Beltis Coronae (B). The topographic rim of Heng-o deforms the local regional plains. An extensive flow field lies to the west, thought to emanate from Beltis Corona (to the NW of Heng-o) and the western annulus of Heng-o. Three volcanic centers of different ages lie within the annulus of Heng-o (portion of C1-MIDR 00N352).

Figure 3b. Sketch map of Heng-o and Beltis Coronae. The interior of Heng-o Corona has three distinct volcanic centers. A and B indicate areas of older deformation which may be representative of an older annulus-forming event.

Figure 3c. Topographic profile of Beltis Corona and the northern and southern rim of Heng-o Corona. Beltis Corona shows a complex interior topography. The northern rim of Heng-o displays both an outer and inner trough, while the southern rim topography of Heng-o shows two inner troughs separated by a ridge.

Figure 3d. Topographic map of Heng-o and Beltis Coronae. Topographic profiles are marked by lines. N and S correspond to the northern and southern section of Heng-o Corona, and B to Beltis: see Figure 3c.

Figure 4a. Magellan image of Silvia Corona. The interior of the corona is composed of elevated relict plains which have been embayed by the younger regional plains. Little volcanism is associated with the formation of the corona (portion of C1-MIDR 15N352).

Figure 4b. Sketch map of Silvia Corona. The center of the corona is interpreted as older relic plains materials. Silvia Corona lacks small-scale annulus structures and volcanism.

Figure 4c. Topographic profile of Silvia Corona. The corona interior is higher than the surrounding plains materials.

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Figure 4c. Topographic profile of Silvia Corona. The corona interior is higher than the surrounding plains materials.

Figure 4d. Topographic map of Silvia Corona. Line corresponds to topographic profile figure 4c.